Frequency-selective surface cloaking for acoustic waves

Mohamed Farhat[1,2], Pai Yen Chen[1], Sebastien Guenneau[3], Stefan Enoch[3], and Andrea Alù [1]

[1]Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX, 78712, USA
Fax: +1.512.471.6598; email: alu@mail.utexas.edu
[2]Institute of Condensed Matter Theory and Solid State Optics, Friedrich-Schiller-Universitat, Jena, Max-Wien-Platz 1, D-07743 Jena, Germany
Fax: +49(0)36419-47152; email: mohamed.farhat@uni-jena.de
[3]Institut Fresnel, CNRS, Aix-Marseille Universite, Campus Universitaire de Saint-Jerome, 13013 Marseille, France

Abstract

This contribution applies the concept of 'mantle cloaking', based on the use of appropriate ultrathin pseudo-surfaces that may act as a cloaking device for a finite range of frequencies, to acoustic waves. The physical principle underlying this technique consists in finding the optimal uniform surface impedance (Z=pressure/velocity for elastodynamic waves) that permits us to cancel the scattered field by a diffracting obstacle placed in the way of an impinging acoustical wave. Our numerical simulations performed for 2D and 3D geometries of both the near- and the far-fields show a significant reduction of the acoustic scattering cross-section over a relatively broad range of frequencies, confirming the possibility of designing surface acoustic cloaks (easier to manufacture and less cumbersome than their bulk counterpart). Potential applications lie in low-observability, camouflaging, non-invasive probing, and related applications.

1. Introduction

Over the past few years, research groups from all over the world have demonstrated the exciting possibilities offered by metamaterials to control electromagnetic, acoustic and elastic waves. After the advent of negative refraction and sub-wavelength imaging [1], it appeared possible to hide some dielectric or conducting objects to electromagnetic radiation and to make them invisible using these exotic materials acting as passive [2]-[5] or active [6] devices.

In this paper, we apply the recent findings on the possibility of making objects invisible using properly designed metasurfaces to acoustic waves in 2-D and 3-D scenarios. In [7] it was shown that a patterned metasurface may produce significant cloaking effects in a simple and ultrathin geometry for electromagnetic waves. This surface cloaking methodology is based on scattering cancellation, for which an ultrathin mantle cloak with an averaged surface reactance (which may be made by frequency selective surface (FSS) [8] or metasurfaces) may tailor the averaged induced surface current density and provide a low visibility comparable to the one achieved by bulk metamaterial cloaks. We thus build on these findings and propose an analogous cloaking mechanism in the context of acoustic waves by using the well-known concept of acoustic impedance.

2. Numerical analysis

Assuming harmonic time dependence, the governing equation for both 2D and 3D acoustic waves is given by:

ISBN 978-952-67611-0-7

$$\nabla \cdot (\rho^{-1} \nabla p) + \frac{\omega^2}{\lambda} p = 0$$

where ρ is the density tensor, λ is the bulk modulus and p is the pressure of the fluid. This equation is supplied with continuity conditions of the pressure and the normal component of the velocity v_r on the different interfaces of the domains of study. Moreover, on the boundary of the cloaking device we consider that the acoustic impedance introduces a discontinuity of the normal velocity:

$$p\big|_{r=a_c} = \frac{v_r\big|_{r=a_c^-} - v_r\big|_{r=a_c^+}}{Z_s}$$

where a_c^+ and a_c^- denote respectively the outer and inner boundaries of the cloak and Z_s is its acoustic impedance.

Figure 1 shows the dependence of the total scattering width on the surface reactance X_s (where we have assumed that $Z_s = R_s + iX_s$, R_s being related to losses) of the mantle cloak for both (a) soft and (c) hard acoustic cylindrical obstacles, where the bare cylinders (gray-dash line) are also shown for comparison. As it can be seen in the figure, for a finite and broad range of values of X_s, a significant scattering reduction is achieved, and we have verified that this may be reproduced for different values of a_c (radius of the cloak), as it can be seen in Fig. 1(a) and (c), even in the limit of a conformal cloak ($a_c = a$). In the limit of large reactances ($X_s \to \infty$), we notice that the patterned surface does not reduce the scattering, which is consistent with the limit of vanishing surface.

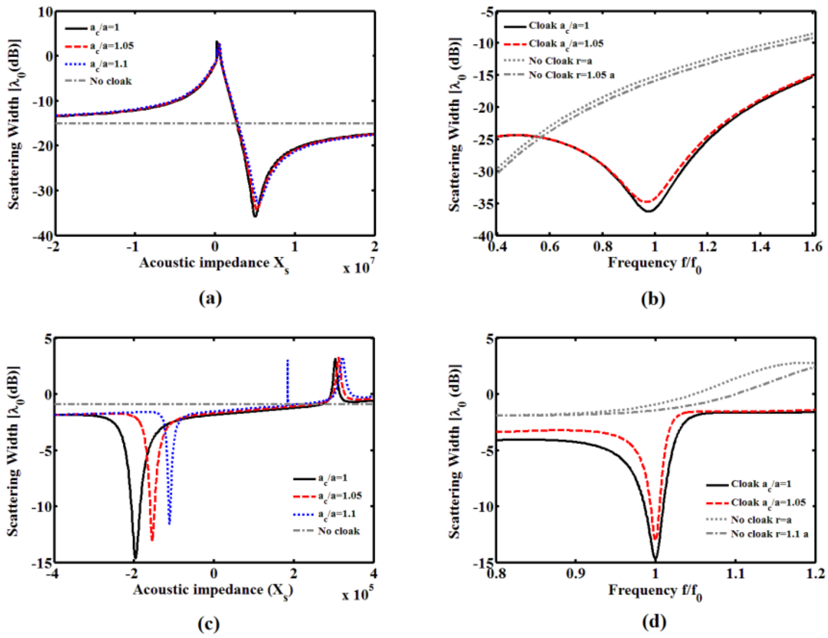

Fig. 1: Variation of the total scattering width (SW) of a: (a) hard ($\lambda_0 = 0.1$) and (c) soft ($\lambda_0 = 10$) cylinder with radius $k_0 a = \pi / 5$ covered by a mantle acoustic cloak, varying its surface reactance; (b) and (d) dispersion of the scattering width versus normalized frequency (λ_0 denotes the relative bulk modulus and k_0 the free-space wave-vector).

We also show in Fig. 2 the far-field behavior of the acoustic mantle cloaks, as the bistatic cross-section patterns at the design frequency for the optimal surface impedance of the cloak, to exemplify the reduction of scattering by the mantle cloak. From these scattering diagrams, it is obvious that the cloaked obstacle is quasi-undetectable at all angles of observation for both soft and hard objects.

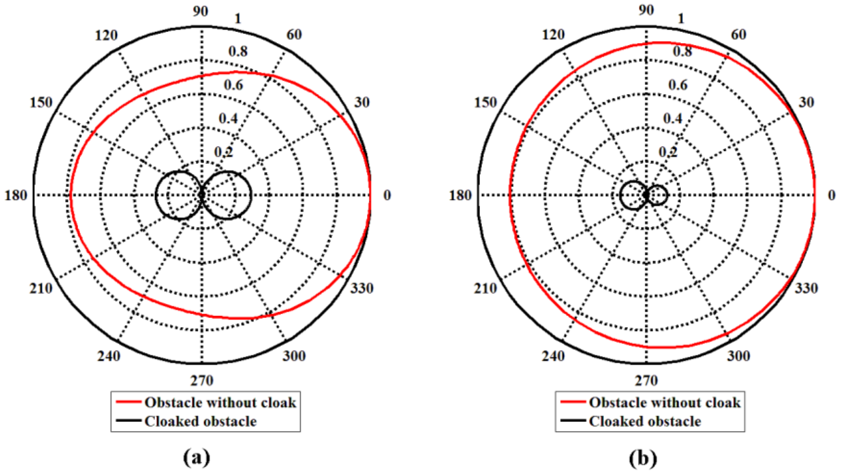

Fig. 2: Far field calculations of the scattered pressure field for the bare cylinder with $\lambda_0 = 10$ [red curve in (a)] and the cloaked cylinder [black curve in (a)]. In (b), we consider the same setup, but for an acoustic cylinder with $\lambda_0 = 0.1$.

4. Conclusion

In the current paper, we have applied the concept of mantle cloaks to acoustic waves [9]. We have studied analytically and numerically a surface impedance cloak that allows drastic scattering reduction from hard and soft cylindrical objects. We have further analysed the mechanisms associated with this acoustic impedance cloak. One may envision that using these FSS may make the realization of thin cloaks closer to its practical and feasible realization for both optical and acoustic waves. We believe that our results may be easily implemented within an experimental setup, for instance by employing thin patterned surfaces with proper reactive response. This mantle cloak may also represent a viable way for noninvasive sensing and probing (ultrasound imaging for example) with improved bandwidth, following the results presented in [10]-[11].

References

[1] J.B. Pendry, Negative refraction makes a perfect lens, *Phys. Rev. Lett.,* vol. 85, p. 3966, 2000.
[2] J.B. Pendry, D. Schurig, and D.R. Smith, Controlling electromagnetic fields, *Science,* vol. 312, 1780, 2006.
[3] U. Leonhardt, Optical conformal mapping, *Science,* vol. 312, p. 1777, 2006.
[4] A. Alù, and N. Engheta, Achieving transparency with plasmonic and metamaterial coatings, *Phys. Rev. E,* vol. 72, p. 016623, 2005.
[5] M. Farhat, S. Enoch, S. Guenneau, and A.B. Movchan, Broadband Cylindrical Acoustic Cloak for Linear Surface Waves in a Fluid, *Phys. Rev. Lett.,* vol. 101, p. 134501, 2008.
[6] F.G. Vasquez, G. W. Milton, D. Onofrei, Active Exterior Cloaking for the 2D Laplace and Helmholtz Equations, *Phys. Rev. Lett.,* vol. 103, p. 073901, 2009.
[7] A. Alù, Mantle cloak: Invisibility induced by a surface, *Phys. Rev. B,* vol. 80, p. 245115, 2009.
[8] B.A. Munk, *Frequency selective surface: theory and design*, New York: John Wiley and Sons, 2000.
[9] P.Y. Chen, M. Farhat, S. Guenneau, S. Enoch, and A. Alù, Acoustic Invisibility via Ultrathin Pseudo-Surface (2 papers in preparation).
[10] A. Alù, and N. Engheta, Cloaking a sensor, *Phys. Rev. Lett.*, vol. 102, 233901, 2009.
[11] A. Alù, and N. Engheta, Cloaked near-field scanning optical microscope tip for noninvasive near-field imaging, *Phys. Rev. Lett.*, vol. 105, 263906, 2010.